

Localized Ignition and Subsequent Flame Spread Over Solid Fuels in Microgravity

T. Kashiwagi¹, Y. Nakamura², K. Prasad¹, H. Baum¹, S. Olson³,
O. Fujita⁴, K. Nishizawa⁴, and K. Ito⁴

¹Building Fire Research Laboratory, NIST, Gaithersburg, MD 20899 USA

²Department of Mechanical Engineering, Nagoya University, Nagoya, Japan

³NASA Glenn Research Center, Cleveland, OH 44135, USA

⁴Department of Mechanical Science, Hokkaido University, Sapporo, Japan

Introduction

Localized ignition is initiated by an external radiant source at the middle of a thin solid sheet under external slow flow, simulating fire initiation in a spacecraft with a slow ventilation flow. Ignition behavior, subsequent transition simultaneously to upstream and downstream flame spread, and flame growth behavior are studied theoretically and experimentally. There are **two transition stages** in this study; one is the **first transition** from the onset of the ignition to form an initial anchored flame close to the sample surface, near the ignited area. The **second transition** is the flame growth stage from the anchored flame to a steady fire spread state (i.e. no change in flame size or in heat release rate) or a quasi-steady state, if either exists. Observations of experimental spot ignition characteristics and of the second transition over a thermally thin paper were made to determine the effects of external flow velocity¹. Both transitions have been studied theoretically to determine the effects of the confinement by a relatively small test chamber², of the ignition configuration (ignition across the sample width vs spot ignition)³, and of the external flow velocity⁴ on the two transitions over a thermally thin paper.

This study is currently extending to two new areas; one is to include a thermoplastic sample such poly(methymethacrylate), PMMA, and the other is to determine the effects of sample thickness on the transitions. The recent results of these new studies on the first transition are briefly reported.

Ignition and First Transition over PMMA

Ignition of a PMMA sheet (14 cm long x 10 cm width) was initiated at its middle by a CO₂ laser having a total power of about 28 W at the sample surface. The sheet was mounted in the middle of the test chamber and exposed to a slow external flow of up to 10 cm/s. Therefore, subsequent flame spread from the localized ignition could occur simultaneously upstream and downstream. There are two flames, one on the irradiated surface and the other on the backside surface. Two different sheet thickness of 0.2 mm and 0.4 mm were used. The experiment was conducted in the 10 s drop tower at the Japan Microgravity Center, JAMIC. Ignition of the PMMA sample was observed shortly after the start of the laser irradiation on the irradiated surface but subsequent ignition of the backside surface (non-irradiated side) was significantly delayed. The delay increases with the thicker sample and lower oxygen concentration as shown in Figure 1. Although the number of the experiments is rather limited, the results show that the backside ignition occurs only after the termination of laser irradiation in 21 % oxygen concentration. The

duration of the laser irradiation could have significant effects on the backside ignition. This was demonstrated in the case of the tests with external velocity of 5 cm/s in 21 % oxygen concentration with two different irradiation times. A 6 s duration did not ignite the backside within the available test time of 10 s while a 3 s duration did ignite the backside within 1 s after the termination of irradiation. The behavior of flame during the first transition to backside ignition and subsequent anchored flame is shown in Figure 2. It is curious that it takes several seconds to ignite the backside in 21 % O₂ concentration, even though there is an open hole through the sample by the laser irradiation shortly after the onset of the front side ignition. After the laser termination, the flame becomes very small and moves close to the sample surface and the open hole. Then, backside ignition

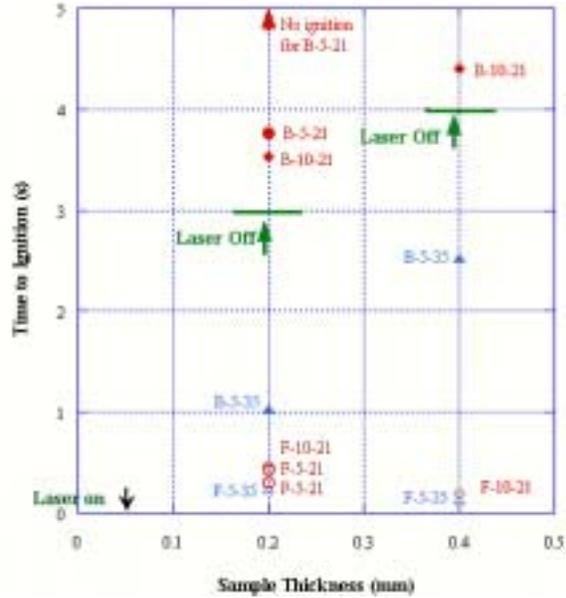


Figure 1. Effects of sample thickness on ignition delay time of PMMA in microgravity. (F-frontside/B-backside)-flow velocity(cm/s)-O₂ concentration.

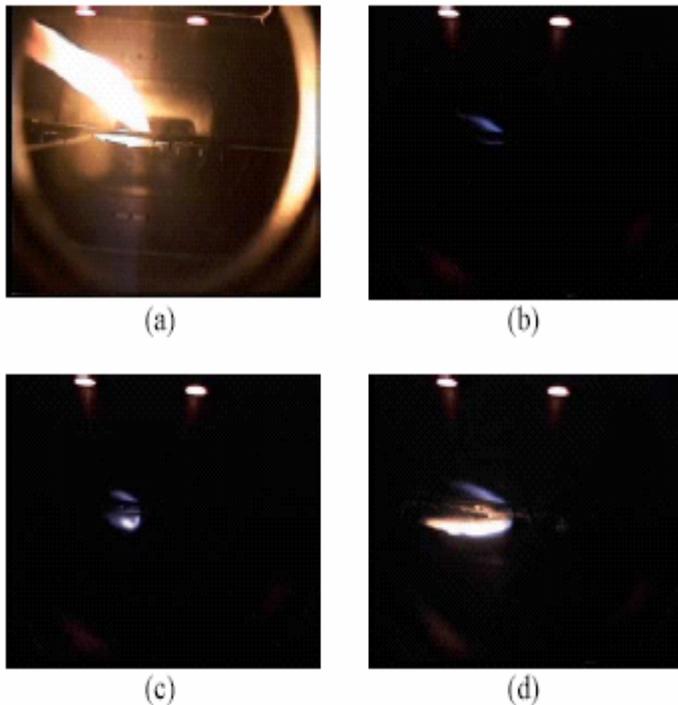


Figure 2. Selected edge view video images of flame behavior over 0.2mm thick PMMA sheet in 21 % O₂ at 10 cm/s flow from right to left. Laser irradiation normal to the sample surface from top. (a) 1.13s, (b) 3.16s, (c) 4.01s, and (d) 7.02s.

occurs.

In 35 % O₂ concentration, the flame is brighter than that in 21 % O₂ concentration and backside ignition occurs before the termination of laser irradiation. Similar flame behavior is also observed with paper samples in microgravity. In normal gravity, delayed backside ignition was observed with the PMMA samples in air under the ceiling configuration (upward laser irradiation normal to a downward facing sample surface). This curious behavior of flame during the first transition will be further studied. Our numerical calculation will be used to understand why such long delay occurs for the backside ignition.

Ignition behavior of the PMMA sheet by a CO₂ laser in zero gravity and also in normal gravity was numerically calculated. The details of our model and computational scheme can be found in our previous publication². The absorption of the incident laser energy by the degradation products from PMMA is included in our three-dimensional, time-dependent code. The results of ignition delay time (irradiated side) in quiescent normal

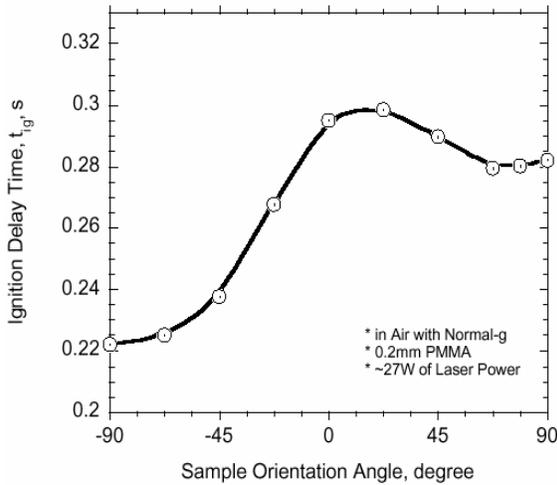


Figure 3. Ignition delay of PMMA (0.2 mm) thick in quiescent normal gravity.

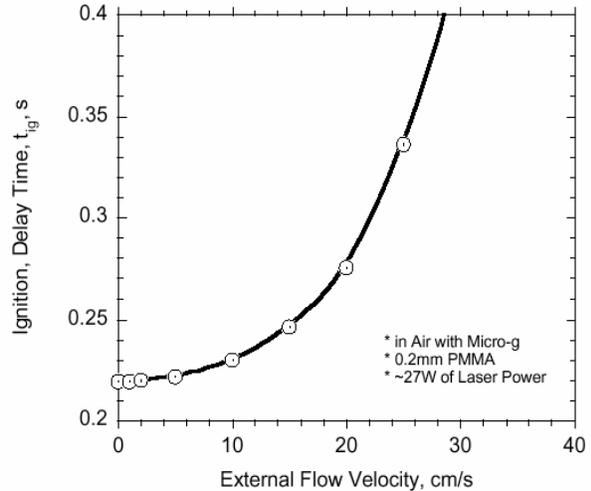


Figure 4. Ignition of PMMA(0.2 mm) in zero gravity.

gravity are shown in Figure 3 as a function of the sample orientation angle. (The sample orientation angle of 0 degree means a vertically mounted configuration and +90 degree means a horizontal upward facing sample.) In this calculation, the laser beam irradiates normal to the sample surface at all angles. The ignition delay time is the shortest at the ceiling configuration (-90 degree) and it increases with an increase in sample orientation angle. However, from about 20 degree to 60 degree ignition delay time tends to decrease with the angle. This decrease is caused by the ignition location moving toward the center of the laser beam. On the other hand, in zero microgravity ignition delay time increases monotonically with an increase in external flow velocity due to blowing away the ignition location from the irradiated area. Ignition behavior on the front (irradiated) surface followed by ignition on the backside surface in zero gravity under an external air flow of 10 cm/s (from right to left) is shown in Figure 5. The calculated results show the

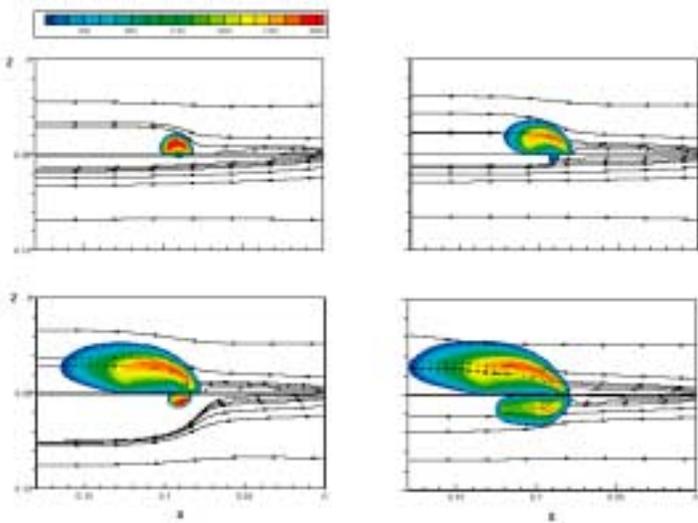


Figure 5. Ignition of the front PMMA surface (0.2 mm thick) followed by ignition of the back surface in microgravity.

flow from the backside to the front side through an open hole generated by the absorption of the laser beam. This flow is generated by the flame on the front surface and this flow could have significant effects on ignition of the backside surface. We are currently studying in detail the transition behavior from the front surface ignition to the ignition of the backside surface.

Effects of the sample thickness on the transitions.

Our numerical code based on the modified version of the Fire Dynamic Simulation code is being extended to apply to a sample of any thickness, removing the thermally thin limitation. For the above results described of PMMA, thermal conduction in the sample is included but not the transport process of the degradation products in the sample. However, for a paper sample, transport processes of degradation products and oxygen, and a convective flux based on the Darcy's law are included to describe the transport processes in the porous paper sample using a porosity parameter. Preliminary results of the first transition from localized ignition to flame spread are shown in Figure

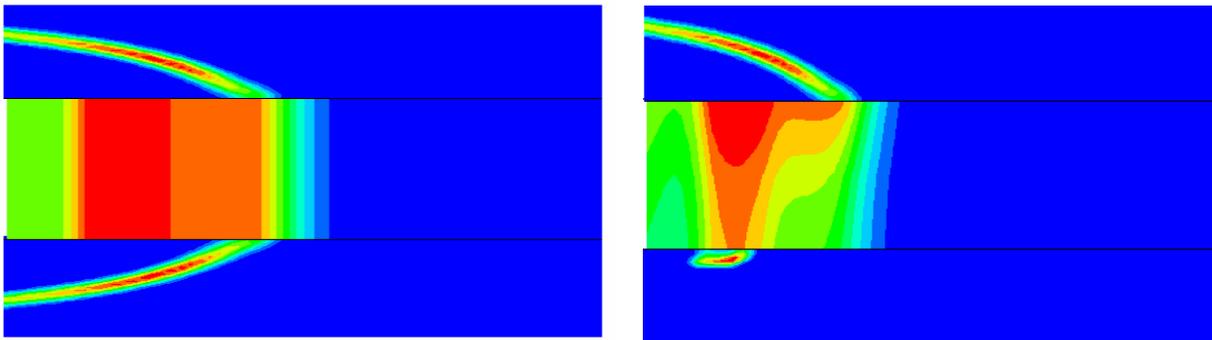


Figure 6. Calculated temperature distribution during the transition from localized ignition to flame spread over a paper based on two case in microgravity, left: thermally thin case and right: general case under external flow of 20 cm/s from right to left. The sample thickness is expanded.

6. For the thermally thin case (includes heat conduction along the sample), flame and subsequent flame spreading appears simultaneously on both sample surfaces. However, for the general case, flame appears at first on the irradiated surface and then on the backside surface with some delay similar to the PMMA case described above. We are currently conducting parametric study to determine under what conditions the species transport processes in the sample become important.

Acknowledgement

This study is supported by the NASA Microgravity Science Program under the Inter-Agency Agreement No. C-32090K and NCC 3-919.

¹ Olson, S.L., Kashiwagi, T., Fujita, O., Kikuchi, M., and Ito, K., *Combust. Flame*, **125**:852-864 (2001).

² Nakamura, Y., Kashiwagi, T., McGrattan, K.B. and Baum, H.R., *Combust. Flame*, **130**:307-321 (2002).

³ Mell, W.E. and Kashiwagi, T., *Proc. Combust. Inst.* **27**:2635-2641 (1998).

⁴ Prasad, K., Nakamura, Y., Olson, S.L., Fujita, O., Nishizawa, K., Ito, K., and Kashiwagi, T., *Proc. Combust. Inst.* **29**, to appear.